SNR-threshold based Adaptive Loading for PAM-Fast-OFDM over Optical Wireless Communications

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Abstract: We propose and experimentally demonstrate the first adaptively-loaded PAM-Fast-OFDM over OWC using a simple yet effective SNR-threshold based loading algorithm. Results show >4-dB sensitivity improvement, and a 5.2-Gbit/s transmission with ~44% capacity enhancement is achieved.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications.

1. Introduction

Conventional radio frequency (RF) technology exhibits various issues, such as overcrowded spectrum and the electromagnetic interference. Optical wireless communications (OWC), while avoiding these issues and exhibiting lower cost, provides an alternative solution for future high-speed wireless access for both indoor and outdoor scenarios [1]. To boost the capacity of the bandwidth-limited OWC systems, different digital signal processing (DSP) schemes have been investigated in the prior works [2-4], including the single-carrier modulation and the orthogonal frequency division multiplexing (OFDM) multi-carrier modulation. Although providing a higher spectral efficiency, OFDM exhibits higher computation complexity because of its complex-valued discrete Fourier transform (DFT) operation. Recently, discrete cosine transform (DCT) based fast-OFDM has been widely investigated in optical systems due to its enhanced robustness to residual frequency offset and improved performance in channel estimation [5-6]. Compared with the conventional DFT-OFDM, all the subcarriers can be used for data modulation without the Hermitian symmetry constraint. Moreover, while maintaining the same transmission performance, only real-valued operations are required for fast-OFDM. As a result, fast-OFDM requires $(N\log_2 N)/2-3N+4$ less multiplications and $(3N\log_2 N)/2-2N+3$ less additions, where N is the block size of DCT [6]. This results in the reduction of both implementation complexity and the corresponding transceiver DSP power consumption. Consequently, Fast-OFDM is an attractive solution for complexity- and power-sensitive applications, such as the data center interconnects and OWC systems. In prior investigations, the system performance was not optimized since only fixed modulation format was used for PAM-fast-OFDM. Considering the uneven system frequency response, especially for the OWC system that suffers from the channel fading and limited system bandwidth, adaptive schemes are preferable for optimizing system performance. To the best of our knowledge, the adaptively-loaded PAM-Fast-OFDM and the corresponding loading algorithm have not been investigated.

In this paper, we propose and experimentally demonstrate the first adaptively-loaded DCT-based PAM-Fast-OFDM. A simple yet effective signal-to-noise-ratio (SNR) threshold based adaptive bit and power loading algorithm for PAM-fast-OFDM is proposed and its effectiveness is experimentally verified. It is demonstrated that similar to the adaptively-loaded QAM-OFDM, a ladder-like SNR profile can also be obtained for the PAM-fast-OFDM by using the proposed loading algorithm, resulting in significantly reduced BER. Experimental results show that for the FEC limit of 3.8×10^{-3}, a data rate of 5.2-Gbit/s transmission can be achieved, with a capacity enhancement of ~44%.

2. Principles and experimental setup

The experimental setup and the DSP block diagram of DCT-based adaptively-loaded PAM-fast-OFDM system are depicted in Fig. 1(a). At the transmitter, after serial-to-parallel (S/P) conversion, one-dimensional pulse-amplitude modulation (PAM) mapping was performed before the inverse DCT (IDCT). After CP insertion and parallel (P/S) conversion, the resulting signal was feed into an arbitrary waveform generator (AWG) for analog PAM-fast-OFDM signal generation. After amplified by an electrical amplifer (EA), the signal together with the DC bias were used to drive a blue laser diode (LD). A convex lens was utilized to collimate the light and the signal was detected by an 1-GHz avalance photodiode (APD) after 2-m free-space transmission. Subsequently, the detected signal was captured by a digital storage oscilloscope (DSO) for offline DSP. The estimated SNR at the channel estimation stage was then used for adaptive bit and power allocation for the PAM-Fast-OFDM. In the experiments, the bias voltage and the gain of the electrical amplifier (EA) for the LD were optimized to 5.3 V and 12 dB, respectively. The block size of DCT was 256, and 255 of the subcarriers (except the DC subcarrier) were modulated with data to maximize the data rate.

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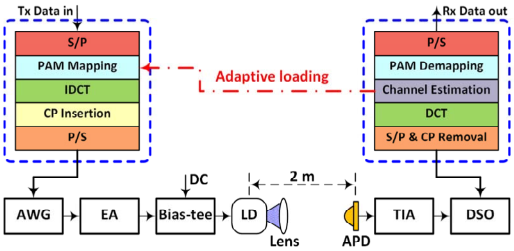
It is worth noting that the conventional SNR-gap based adaptive loading algorithm is not applicable for PAM-fast-OFDM, as there is no generalized BER approximation of *m*-PAM formats for SNR gap calculation. Although it is possible to use symbol-error rate (SER) for SNR gap calculation, as numerically investigated in [7], the resulting loading allocations are sub-optimal. It is because the bit and power are allocated to optimize the SER but not the BER, hence the system will exhibit worse BER performance for higher-order PAM formats. In this work, we propose a simple yet effective SNR-threshold based adaptive loading algorithm, with the aim of minimizing the BER while maintaining the same transmission capacity. Fig. 1(b) shows the pseudo code of the proposed adaptive loading algorithm. Firstly, we theoritically investigate the BER of PAM-fast-OFDM over AWGN channel, and the results are given in Fig. 2(a). For the 20% SD-FEC threshold of 2×10^{-2}, the theoritical SNR values for PAM2 to PAM32 are 6.4 dB, 13.4 dB, 19.4 dB, 25.4 dB, and 31.2 dB, respectively. The corresponding SNR values for the 7% HD-FEC threshold of 3.8×10^{-3} are 8.6 dB, 15.6 dB, 21.8 dB, 27.8 dB, and 33.6 dB, respectively. After obtaining the SNR threshold values, the proposed adaptive loading can be implemented. The proposed loading algorithm is divided into the following three steps: 1) rough bit allocation based on the obtained SNR thresholds; 2) bit re-allocation to maintain the same capacity, as well as to minimize the BER; and 3) power allocation according to the bit allocation results obtained in the second step. In the following investigations, two different BER FEC limits, namely, 2×10^{-2} and 3.8×10^{-3}, will be used to verify the robustness and effectiveness of the proposed adaptive loading algorithm for PAM-fast-OFDM.

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Inputs:  Estimated CSI: SNR                                     Number of data subcarriers: N_sub
         SNR thresholds Γ = [Γ_PAM2, Γ_PAM4, Γ_PAM8, Γ_PAM16, …]  Target number of bits: B_target
Outputs: Bit allocation result: bit_alloc        Power allocation result: power_alloc
Step 1:  for all subcarriers, perform the following initial bit allocation:
             if   SNR_k < Γ_PAM2        diff_SNR_k = SNR_k & temp_bit_k = 0                       else
                  temp_diff_SNR = [SNR_k-Γ_PAM2, SNR_k-Γ_PAM4, SNR_k-Γ_PAM8, SNR_k-Γ_PAM16, …]
                  [diff_SNR_k, temp_bit_k] = min (temp_diff_SNR(temp_diff_SNR ≥ 0))               end
         calculate the total bits after initial bit allocation:     total_bit = sum (temp_bit)
Step 2:  while (total_bit > B_target) do
             subtract one bit at a time from temp_bit on the subcarrier that has the smallest diff_SNR,
             adjust diff_SNR for the specific subcarrier, and re-compute total_bit                 end
         while (total_bit < B_target) do
             add one bit at a time to temp_bit on the subcarrier that has the largest diff_SNR,
             adjust diff_SNR for the specific subcarrier, and re-compute total_bit                 end
Step 3:  bit_alloc = temp_bit & allocate power for each subcarrier according to bit_alloc and SNR_k
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Fig. 1. Experimental setup and the corresponding DSP blocks of the OWC system (left), and the pseudo code of the proposed SNR-threshold based adaptive bit and power loading algorithm for PAM-fast-OFDM (right).

3. Experimental results

We first investigate the BER and SNR performance of the PAM-fast-OFDM over the OWC system, which will be used as the benchmark to evaluate the performance improvement for the proposed scheme. The SNR profile and the constellation diagram of the 2.2-GBaud PAM4-fast-OFDM (the data rate = ~4.4 Gbit/s) are given in Fig. 3(a), and the corresponding BER is 7.10×10^{-3}. Note that the SNR fading around the DC is from the DC blocking effect of the EA, while the fading at high frequencies is attributed to the limited bandwidth of transceivers. The inset of Fig. 3(a) shows the recovered PAM samples vs. the subcarrier index. Clear opening can be observed for samples at the subcarriers in high SNR regions. Apparently, the BER performance of the OWC system is limited by the fading issue. Therefore, by adopting the proposed adaptive bit and power loading algorithm in the PAM-fast-OFDM OWC system, significant BER reduction can be achieved. Fig. 2(b) and Fig. 2(c) show the corresponding bit and power allocation results for 4.4-Gbit/s PAM4-fast-OFDM, when two different SNR thresholds are utilized. It can be seen that similar to the conventional QAM-OFDM case, more bits will be allocated to the subcarriers with higher SNRs. The power distribution exhibits a saw-tooth behavior, in order to maintain a similar BER for subcarriers with the same PAM format.

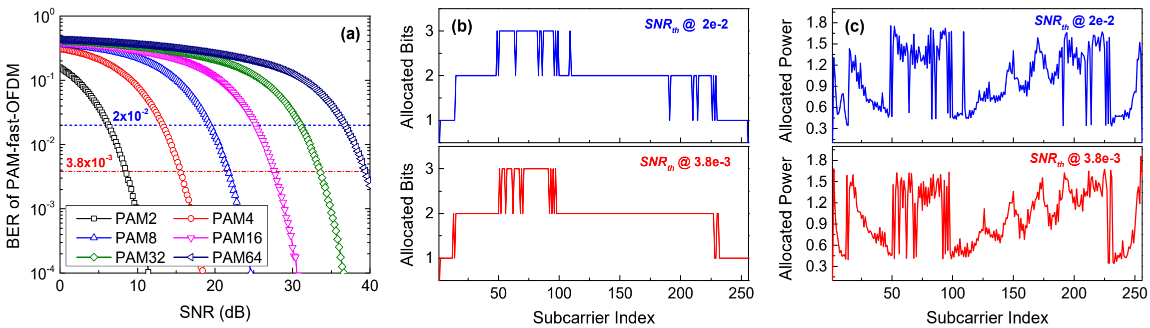

Fig. 2. (a) Theoretical BER of PAM-fast-OFDM; (b) bits, and (c) power allocation results, of the proposed SNR-threshold based adaptive loading algorithm with different SNR thresholds. The data rate is 4.4 Gbit/s and the received optical power is 13.5 dBm. Note the spectral efficiencies of PAM2, PAM4, and PAM8 based fast-OFDM equals to those of QAM4, QAM16, and QAM64 based conventional DFT-OFDM.

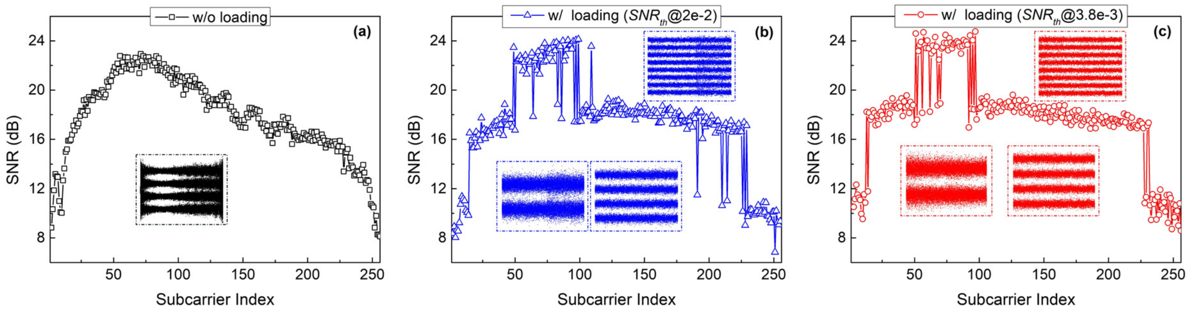

Fig. 3. SNR profiles and the corresponding constellation diagrams of the 4.4-Gbit/s OWC system: (a) without the proposed loading algorithm; (b)&(c): with the proposed loading scheme when SNR_{th} corresponds to 2×10^{-2} and 3.8×10^{-3}, respectively.

The effectiveness of the adaptive loading is verified via experimental transmission, and the corresponding results are given in Fig. 3(b) and Fig. 3(c). Generally, ladder-like SNR profiles are achieved for both SNR-threshold cases. Relatively uniform SNRs can be obtained for the subcarriers with the same PAM format, confirming the feasibility and robustness of the proposed SNR-threshold based adaptive loading algorithm for PAM-fast-OFDM. Results show that comparable BER reduction can be achieved by using the proposed loading algorithm with different SNR thresholds. With the proposed adaptive loading schemes, BER of the 4.4-Gbit/s OWC system can be reduced from 7.10×10^{-3} to 5.05×10^{-4} and 4.16×10^{-4} for SNR thresholds corresponding to 20% and 7% FEC limits, respectively.

We further investigate the performance of the proposed scheme under different baud rate with the sampling rate of AWG varying from 1.8 GSa/s to 2.6 GSa/s. The BER comparison of PAM4-fast-OFDM and the corresponding adaptively-loaded PAM-fast-OFDM (with the same capacity) is given in Fig. 4(a). By using the proposed adaptive loading algorithm, the data rate can be improved from 3.6 Gbit/s to 5.2 Gbit/s at BER = 3.8×10^{-3}, resulting in around 44.4% capacity enhancement. The effectiveness of the proposed scheme is further investigated under different received optical power (ROP). Fig. 4(b) shows the results when the ROP is reduced from 13.5 dBm to 4 dBm for 2-Gbit/s and 4-Gbit/s PAM4-fast-OFDM and the proposed adaptively-loaded PAM-fast-OFDM. As shown in Fig. 4(b), significant BER reduction is achieved. For 4-Gbit/s case, ~4.5-dB sensitivity improvement can be obtained.

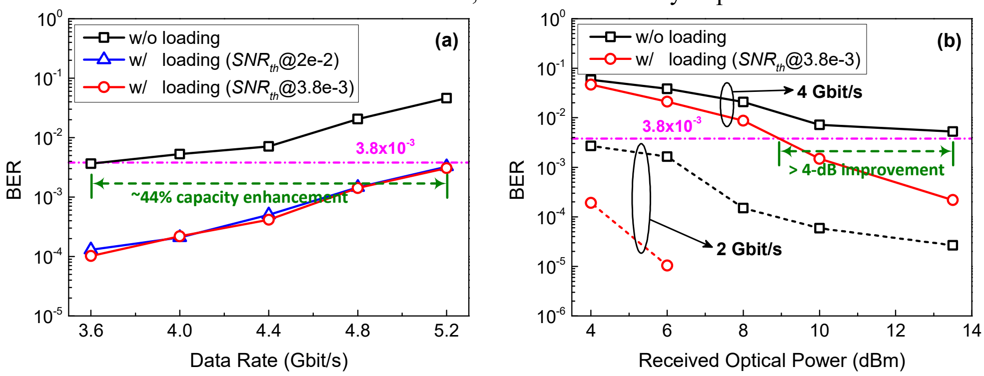

Fig. 4. (a) BER versus different baud rate at 13.5-dBm ROP (b) BER versus different ROP for 2-Gbit/s and 4-Gbit/s PAM-fast-OFDM.

4. Conclusion

In this paper, an adaptively-loaded PAM-fast-OFDM using a simple yet effective SNR-threshold based adaptive loading algorithm, is proposed for OWC. Experimental results show significant BER reduction by using the proposed scheme. More than 4-dB sensitivity improvement and ~44% capacity enhancement are demonstrated. The proposed adaptively-loaded PAM-fast-OFDM scheme provides an attractive solution for high-speed and low-complexity OWC systems. *This work was supported in part by HKSAR RGC grant (GRF 14215416) and Science Foundation Ireland grant 15/CDA/3652.*

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